Multidimensional Simulations of Core Collapse Supernovae

NCCS USERS MEETING

Anthony Mezzacappa, ORNL

March 27, 2007

Core Collapse Supernovae

What are they?

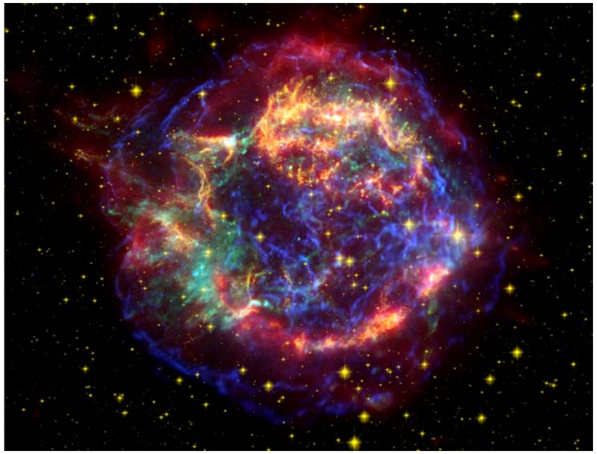
⇨ Explosions of massive stars.

How often do they occur?

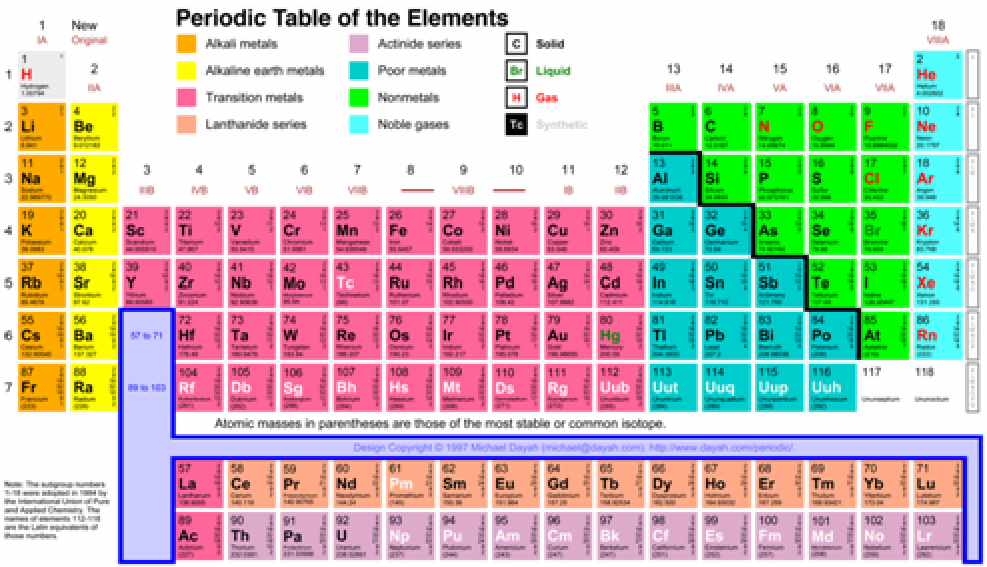
⇨ About twice per century in our galaxy.

Why are they important?

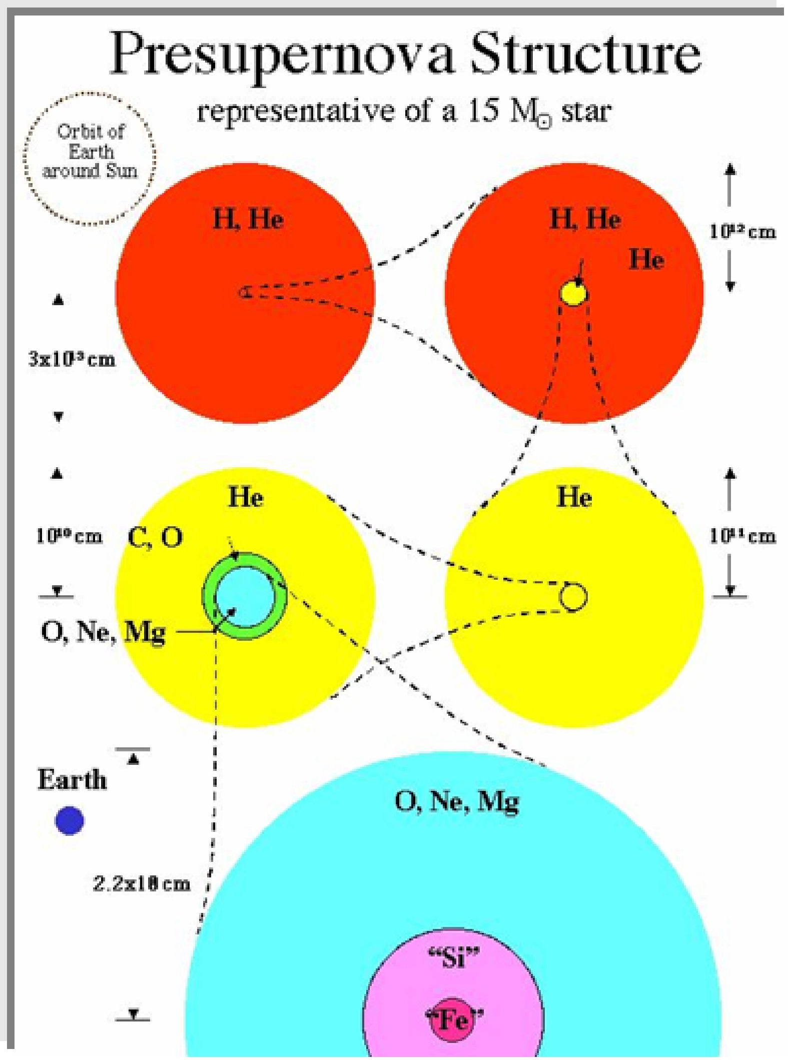
⇨ Dominant source of elements in the Universe.

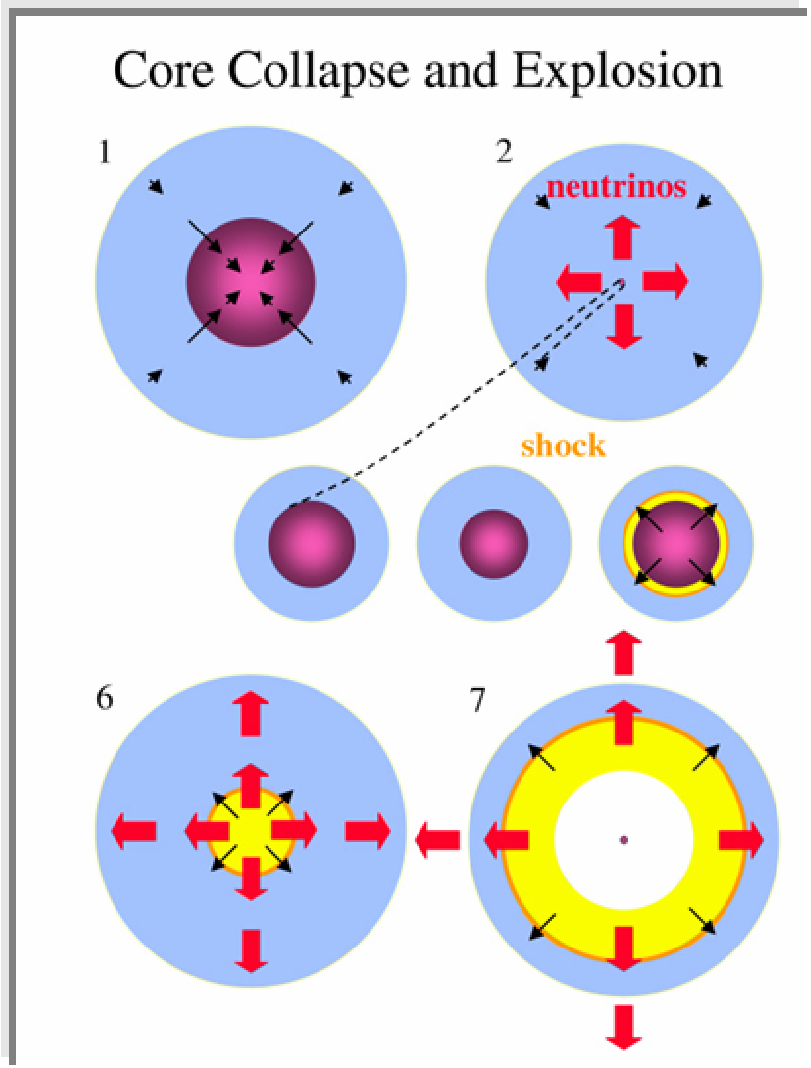


Cas A
Supernova
Remnant
(Chandra Observatory)

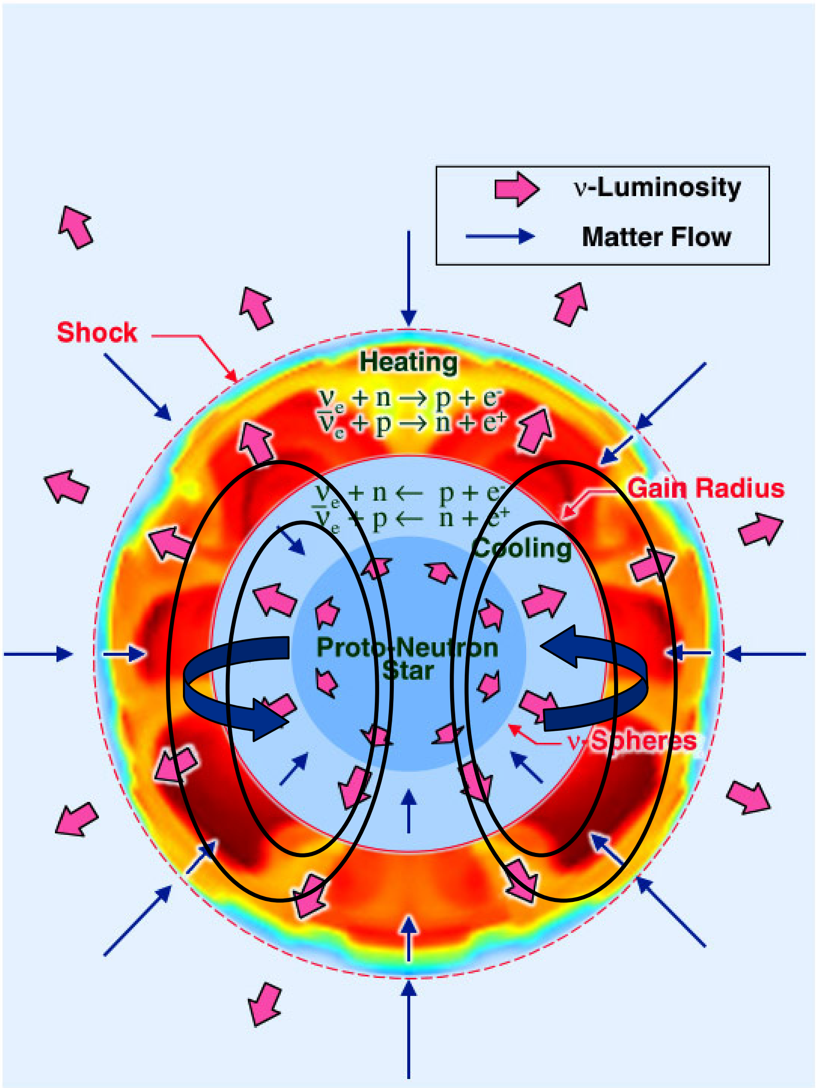


Core Collapse Supernova Paradigm





How is the supernova shock wave revived?



Most fundamental question in supernova theory.

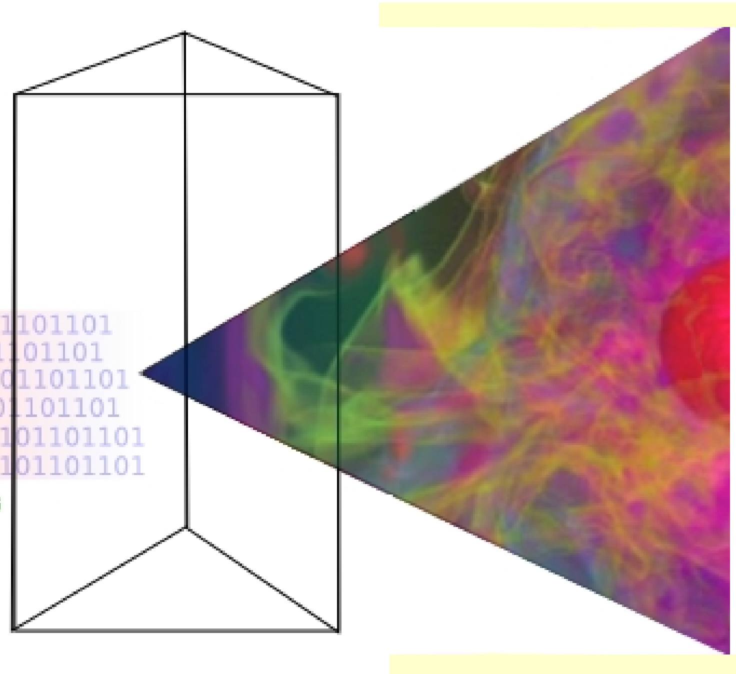
- Gravity
- Neutrino Heating
- Convection
- Shock Instability
- Nuclear Burning
- Rotation
- Magnetic Fields

New Ingredient

Project Overview

- **(CHIMERA) Project Participants**
  - Stephen Bruenn (Florida Atlantic University)
  - John Blondin (North Carolina State University)
  - W. Raphael Hix (ORNL)
  - Bronson Messer (ORNL)

  - Part of larger **PRISM** project.
    - CHIMERA (“Ray-by-Ray” Multifrequency Neutrino Transport)
    - V3D (3D Multifrequency Neutrino Transport)
    - GenASiS (3D Multiangle, Multifrequency Neutrino Transport)
- **Project Overview**
  - Perform 3D multiphysics simulations of core collapse supernovae with multifrequency (multiangle, multifrequency) neutrino transport.
- **Project Milestones**
  - FY07: “Late-time” simulations in 2D.
  - FY07/08: First simulations in 3D with multifrequency neutrino transport.



PRISM

PETASCALE RESEARCH IN INTEGRATED SUPERNOVA MODELING

OAK RIDGE National Laboratory

NC STATE UNIVERSITY

Blondin

Cardall
Hix
Messer
Mezzacappa

UCSD

Fuller
Hayes

FAU

Bruenn
Marronetti

STONY BROOK STATE UNIVERSITY OF NEW YORK

Myra
Swesty

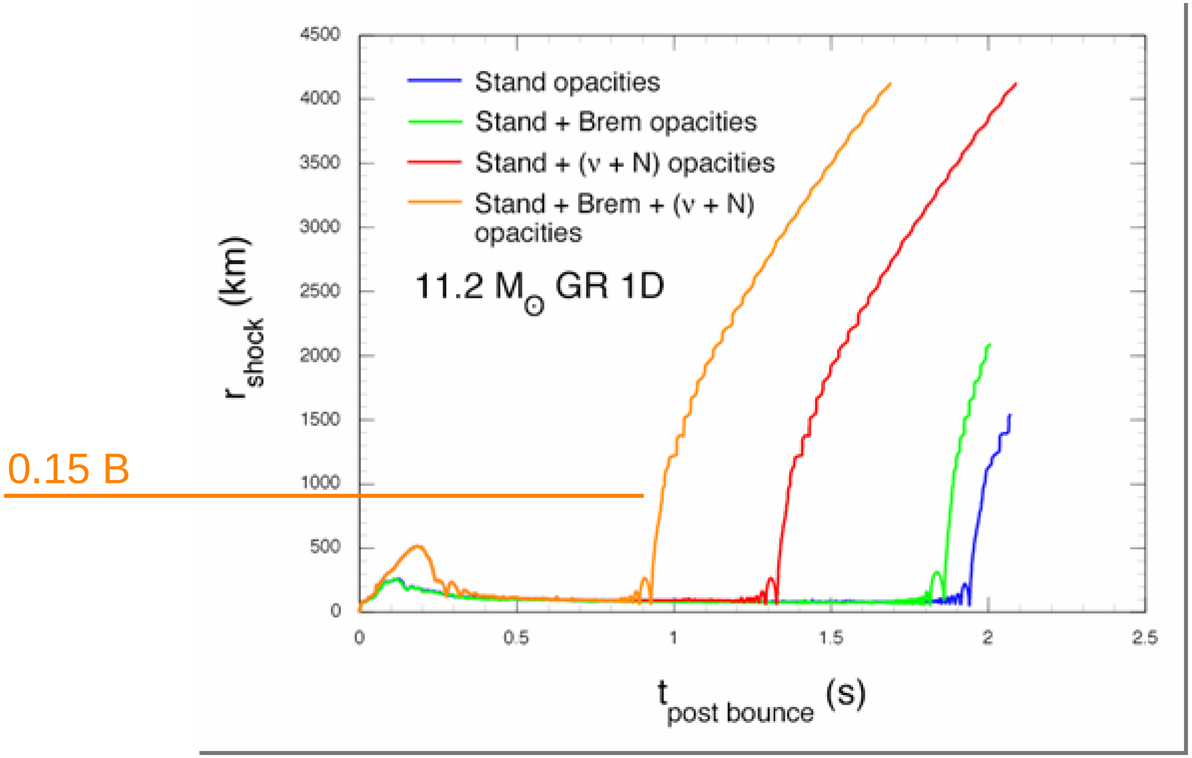
1D Revisited

<u>Simulation Building Blocks</u>

⇨ MGFLD Neutrino Transport
⇨ PPM Hydrodynamics
⇨ GR
⇨ Lattimer-Swesty EOS
⇨ Alpha Network

<u>Resolution</u>

Spatial: 256
Energy: 20



Bruenn et al. (2007)

<u>Findings</u>

- Explosions in 1D.
- Shock is not revived in the iron core.
  ➲ Explosions initiated when shock reaches oxygen layer.

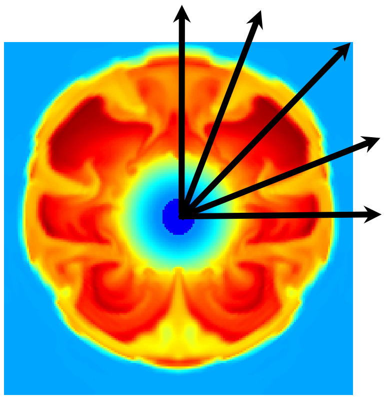
- Time to explosion dictated by efficiency of neutrino heating.

Ongoing 2D Multi-Physics Supernova Models

☐Simulation Building Blocks

- *"RbR-Plus" MGFLD Neutrino Transport*
- *2D PPM Hydrodynamics*
- *Lattimer-Swesty EOS*
- *Nuclear (Alpha) Network*
- *2D Newtonian Gravity with Spherical GR Corrections*
- *Neutrino Emissivities/Opacities*
  - ➲ *"Standard" + Elastic Scattering on Nucleons*
    + Nucleon–Nucleon Bremsstrahlung

✶ Run for postbounce times > 500 ms.
✶ Run on a 180 degree grid.



"Ray-by-Ray" Approximation

- Radial transport allowed.
- Lateral transport suppressed.

Distinguish our 2D runs from runs performed by other groups.

Stellar Mass	Gravity	Opacities	Resolution 20 Groups	t (ms pb)	Explosion	Energy (B)
11	N	Standard	192 X 32	610	Y	0.18
11.2	N	Improved	256 X 128	262	Y	0.1
11.2	N	Improved	256 X 256	429	Y	0.36
11.2	GR	Standard	256 X 256	589	Y	0.19
11.2	GR	Improved	256 X 128	319	Y	0.27
11.2	GR	Improved	256 X 256	372	Y	0.30
15	N	Standard	192 X 32	680	Y	0.14
15	☐N	Improved	256 X 256	269		
15	GR	Improved	256 X 256	180		
20	N	Improved	256 X 256	379	Possible	
20	GR	Improved	256 X 256	307	Possible	

Compare 1D case.

Bruenn et al., *Journ. Phys. Conf. Ser.*, **46**, 393 (2006); Mezzacappa et al., Cefalu' 2006, in press

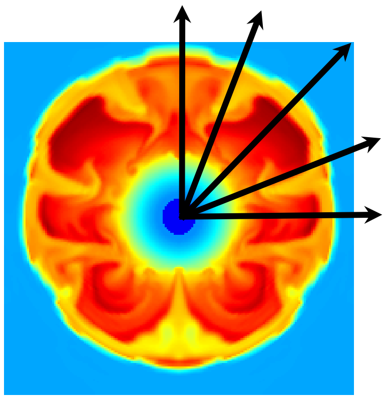
Project Impact

- **What can be solved from the results?**
  - Late time 1D/2D simulations have altered the shock revival paradigm.
  - The trends are promising.
    - Explosions in 1D for lighter progenitors.
    - Faster, more energetic explosions in 2D, perhaps for larger progenitors.
    - What will 3D bring?
- **Who cares about this work and its results? Why?**
  - See Slide 2 for overall motivation.
  - Above results demonstrate we are closing in on the core collapse supernova explosion mechanism.

Project Logistics

- **What size production jobs will you be running?**
  - See next slide.
- **Do you have any special requirements (software/libraries/data storage/scientific workflow)?**
  - Multi-core–aware libraries for sparse linear system solution.
  - 10 to 100 TB per simulation.
- **Do you have any special visualization needs?**
  - Rendering of stellar core fluid composition and magnetic fields in 3D.
  - Rendering of 4D neutrino data (3D plus neutrino energy).

3D Simulation Layout



$$N_{\text{cores}} = N_{\text{rays}} = N_{\theta} \times N_{\phi}$$

Number of Rays	Latitudinal Zones	Longitudinal Zones
8,192	64 (3-Degree Resolution)	128 (3-Degree Resolution)
73,728	192 (1-Degree Resolution)	384 (1-Degree Resolution)

Runtime for mCHIMERA: ~11 days per run at 1 ray per core.
(~22 days at 2 rays per core, etc.)

Project Logistics (continued)

- **What development efforts are required?**
  - 3D-grid issues remain and will require continued work.
  - Parallel I/O performance must be explored.
  - Multi-core–aware linear system solution must be explored.
- **What issues/problems do you anticipate as you begin production?**
  - Achieving reasonable wall-clock throughput for our 3D runs.
    - *What can be done to mitigate the impact of an aggressive architecture-augmentation plan on the production of new science?*
- **What level of interaction do you anticipate with the NCCS staff?**
  - Significant (embedded), particularly with members of the NCCS Scientific Computing Group (Messer).

New Science at 119 TF, 250 TF, 1 PF, Sustained PF

Machine	2D Science	3D Science	Motivation
119 TF		3-Degree Resolution Small Nuclear Network CHIMERA	First 3D Models with Multifrequency <u>Neutrino Transport</u> Explosion Mechanism
250 TF	GenASiS	3-Degree Resolution Large Nuclear Network CHIMERA	Element Synthesis
1 PF		1-Degree Resolution Large Nuclear Network CHIMERA	Higher Resolution *and* Large Nuclear Network
Sustained PF		GenASiS	Definitive Core Collapse Supernova Simulations

Give Praise, Give Thanks

- Doug Kothe: NCCS Leadership
- Ricky Kendall: SCG Leadership
- Bronson Messer: Perfect Example of a Perfect Model
- Sean Ahern, Ross Toedte: Visualization Support

- Buddy Bland: LCF Leadership

- Julia White: NCCS/LCF Public Face

These folks will listen!
In this regard, you will find no better place to compute.